Progress on the Stellarator Path to Fusion Power

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Motivation: Why Stellarators ?

Stellarators potentially provide a path to a reduced cost, compact fusion system

- Eliminate disruptions
- Eliminate external current-drive and need to improve CD efficiency
- Reduced recirculating power, improved system efficiency
- Smaller balance of plant (due to low recirculating power)
- Static or slowly varying magnetic field, simplifying superconducting coils

What is New?

W7-X has validated much of its design optimization

- Neoclassical transport can be designed to be small, sub-dominant
- Then: turbulent transport dominates, *just as in tokamaks*
- Dominantly ITG (Ion Temperature Gradient) & TEM (Trapped Electron)
  Successfully modeled by same theory & codes used for tokamaks
- H (ISS04) = 1.4 with pellet fueling & peaked density profiles
- Divertor design validated. Stable detached operation achieved.

LHD has achieved high plasma parameters in D operation

- Ti(0) ~ Te(0) = 10 keV (at low density)
- Beta up to 3.5% at low collisionality B=1 T. Up to 5% at B=0.4 T

US Activities Focused on Gap Reduction

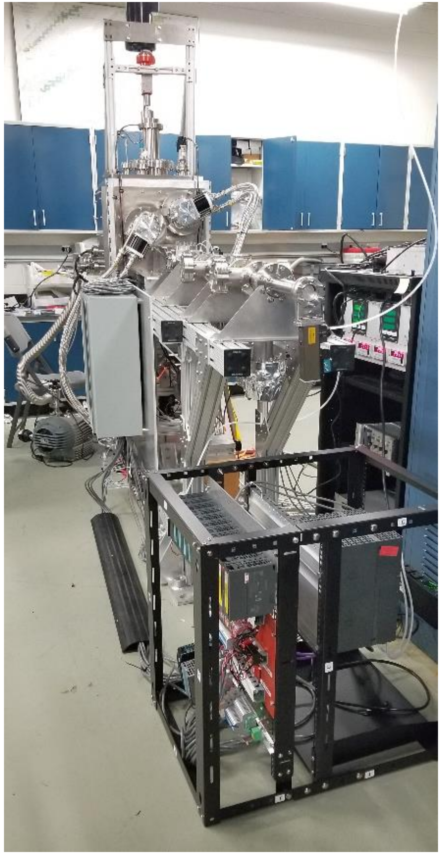
Examples Include

- Reduce turbulent transport, increase plasma confinement
- Optimize fast ion confinement
- Simplify magnet coils for 3D Stellarator shaping
  - Reduce costs, improve maintenance access

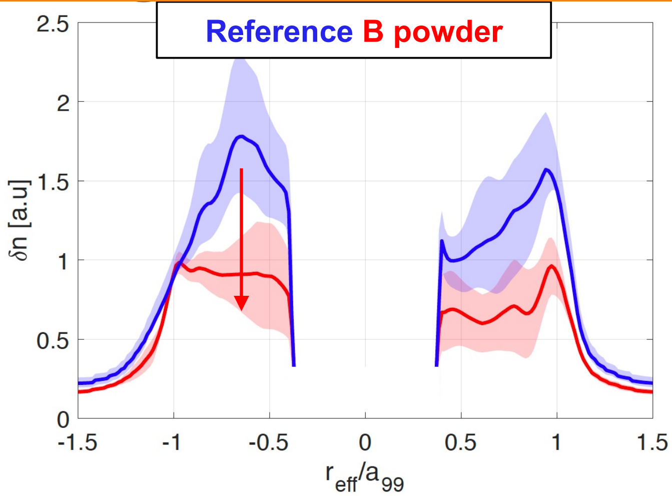
Develop new stellarator fusion plant designs with improved optimization

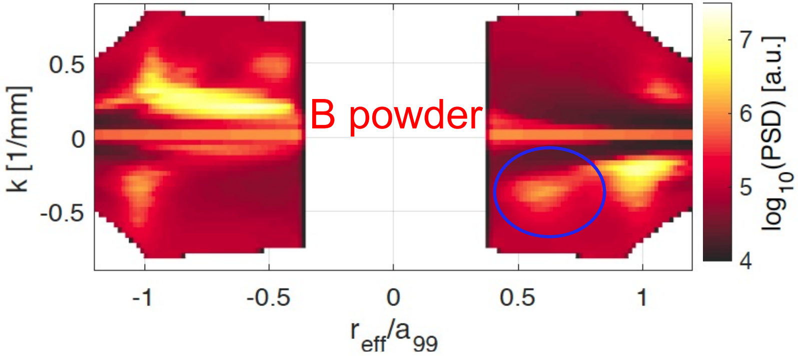
Continuous Pellet Injector for W7X

- Ready for 2022 campaign.
- Continuous pellet fueling (30 min@ 10 Hz) 600-1200 m/s.
- Collaboration of ORNL, PPPL, IPP, NIFS
- Density profile control via pellet fueling for turbulent transport optimization
- Link real-time diagnostics with pellet control

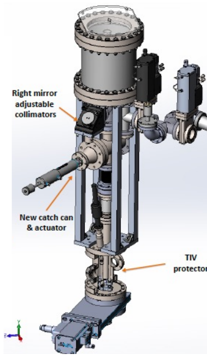


Boron Powder Injection in LHD -> Strong Reduction of Turbulence, Increased Confinement





- Turbulent density fluctuation amplitude decreased by 2 times (PCI), perpendicular velocity doubled in the edge
- Before injection, peak of fluctuation for $k_\perp \sim 0.3$ mm^{-1}, consistent with ITG turbulence [Nunami 2011, Tanaka 2020]
- Suppressed during B injection, together with higher $k_\perp$ fluctuations



- Thermal diffusivities reduced by up to 50% in edge
- T_e, T_i increased ~25%

F. Nespoli et al, accepted Nature Physics

HSX Upgrade: Higher B, P-ECH, density

Magnetic field increasing to 1.25T

New Gyrotron

- 70 GHz, 500 kW gyrotron donated by IPP Greifswald
- X2 mode operation at 1.25 T
- Cut-off density: **3.0 x 10^{19}/m^3**

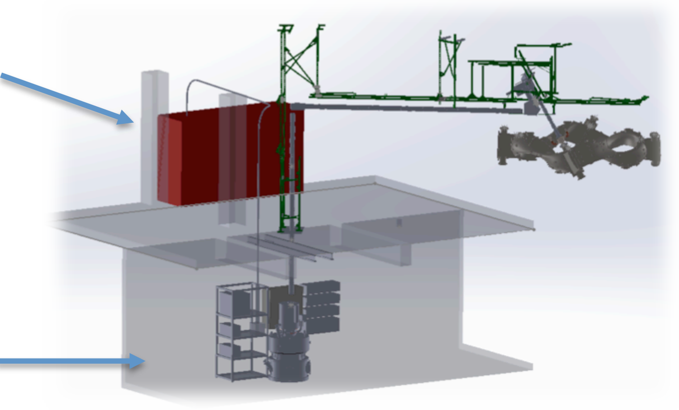
  → operation planned with 2 x 10^{19}/m^3
- Good absorption expected (> 90%)

New power supply installed

- Installation of a 60 kV power supply

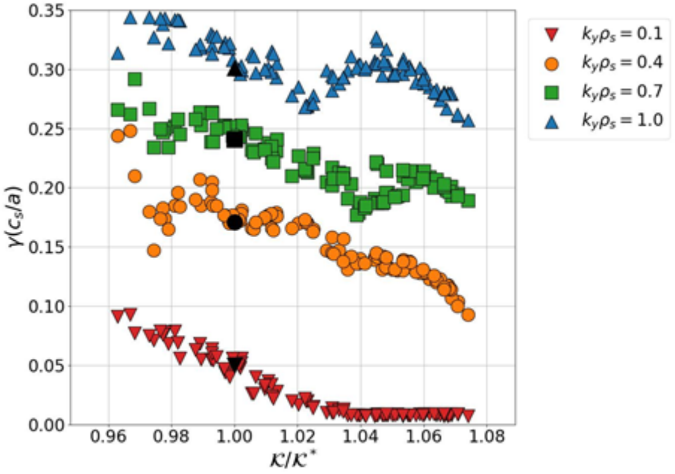
New transmission line designed

“HSX Upgrade” will be completed early in 2022.
→ Studies of the density profile and its impact on TEM

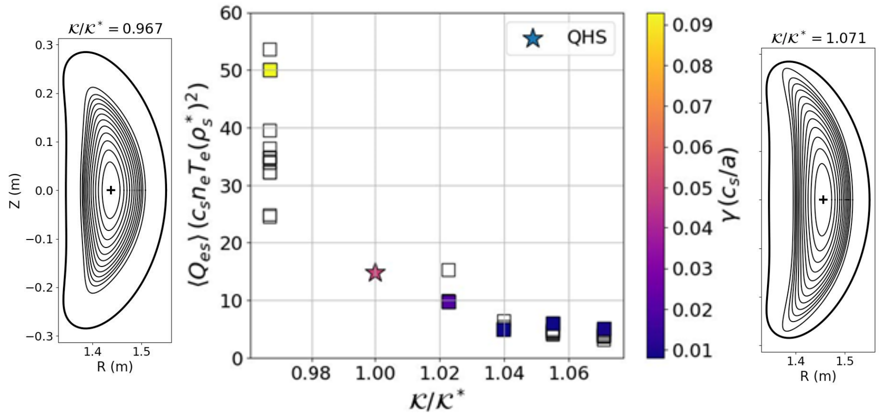


GENE predicts TEM Turbulent Transport can be Reduced in HSX

- Linear GENE simulations for 100 configurations show strong correlation between plasma elongation and TEM growth rates



- Elongation can be controlled by coil-currents
- Non-linear heat fluxes from GENE simulations decrease with elongation (about 3-times lower than standard QHS)



Optimization of HSX TEM via coil-currents appears to be possible and will be tested experimentally!

Courtesy M. Gerard, APS 2021

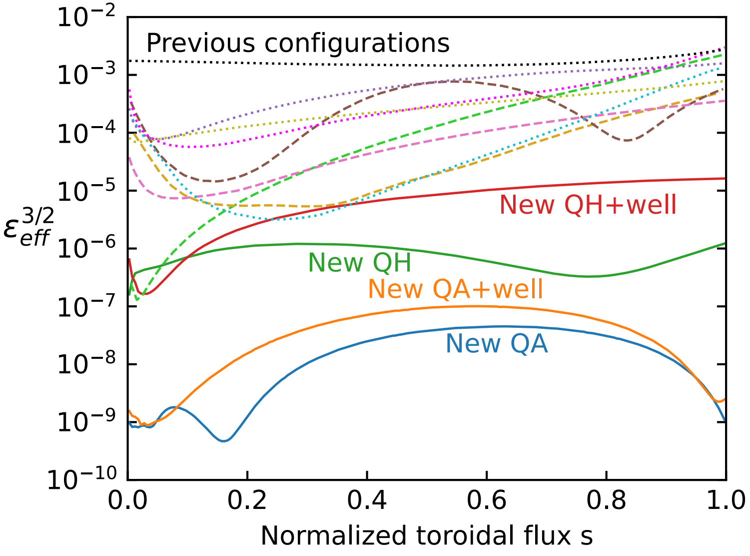
Hidden Symmetries Project: Improved Stellarator Optimization

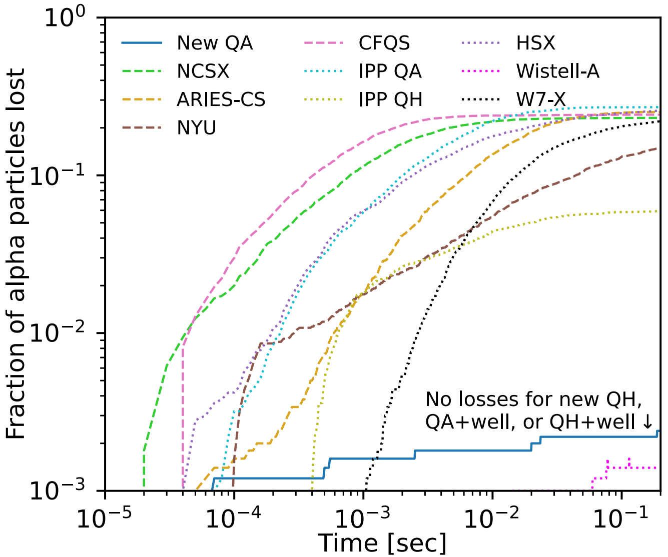
Objective: To create and exploit an effective mathematical and computational framework for the design of stellarators with hidden symmetries.

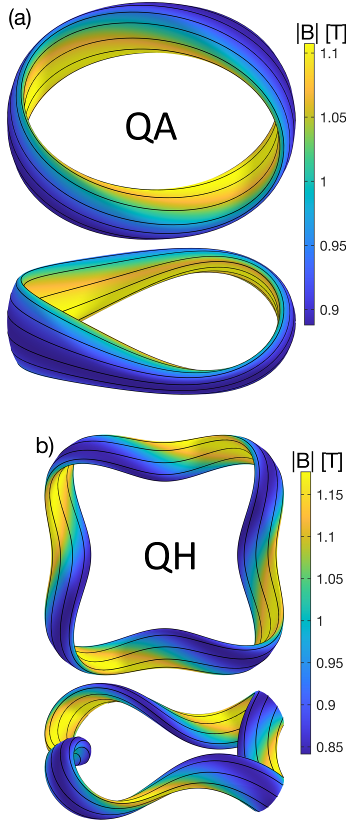
- International interdisciplinary collaboration: plasma physics, optimization theory, dynamical systems and PDE theory.
- From fundamental results to computational tools to experimental designs.
- A new optimization code (*SIMSOPT*, *SIMonS OPT*imization code) that can exploit the full power of parallel computers
- New techniques, such as adjoint methods and automatic differentiation
- Designs of next-generation stellarator experiments.

Supported by the Simons Foundation

New Optimization Approaches: Precise Quasi-Symmetry







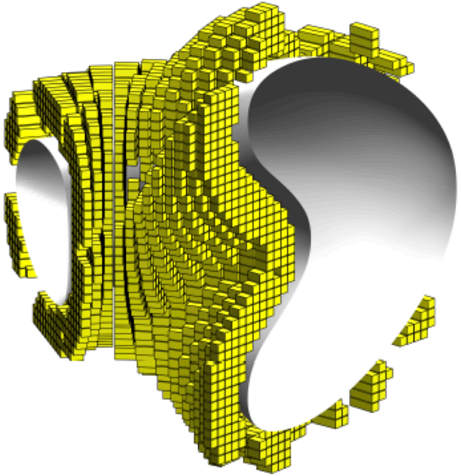
- New optimization algorithms & code (SIMSOPT) is able to achieve extremely good quasi-symmetry (fixed boundary)
- Better neoclassical optimization than all existing designs and experiments, over whole plasma cross-section
- Also achieves ideal fast ion confinement – no loss !
- Next focus is turbulent transport optimization

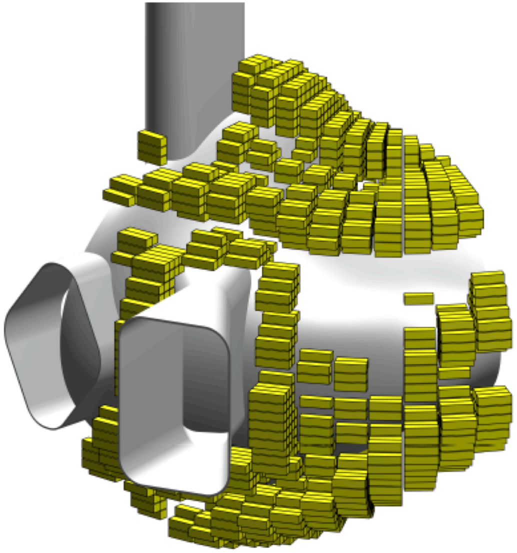
M.Landreman & E.Paul arXiv:2108.03711v2

Simplify Coils: Permanent Magnets for Shaping

PM4STELL Project:

- Construct ½-period of a 3-period QA stellarator as <u>engineering test</u>
- Reuse NCSX vessel & planar TF coils
- Expected permanent magnet thickness ~25 cm for B_T=0.5 T
- Improve physics properties over NCSX, particularly fast ion confinement

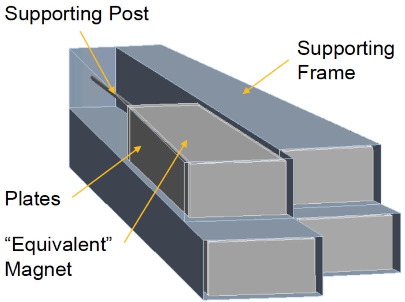




Start construction in 2022.

Funded by ARPA-E, FES, Stellar Energy Foundation

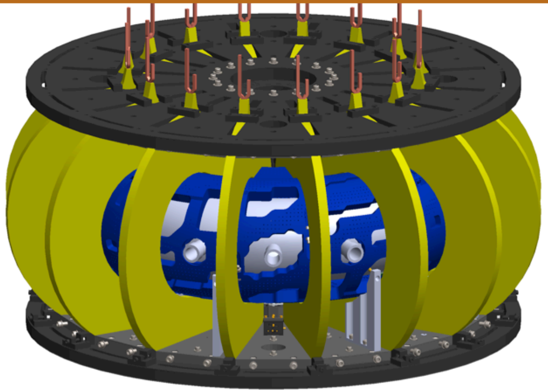
Assembly concept "Post-office Box"

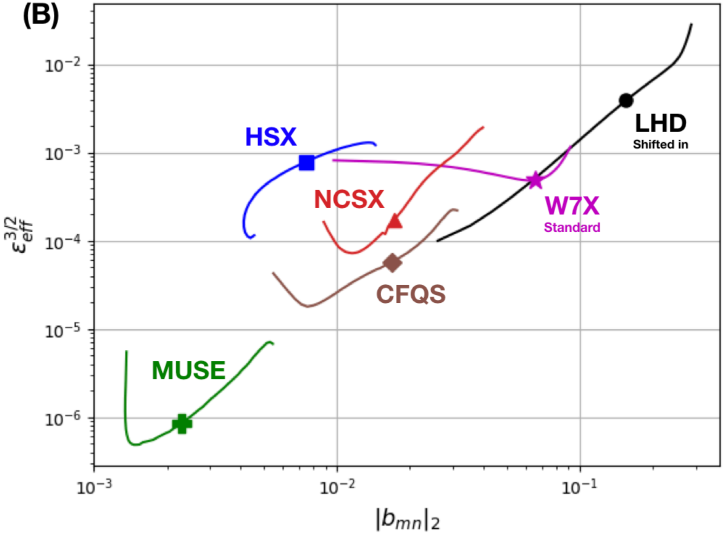


PPPL PRINCETON PLASMA PHYSICS LABORATORY

MUSE: Optimized Stellarator with Simple Coils

- Inexpensive Quasi-Axisymmetric (QA) highly optimized stellarator
- |B| independent of toroidal angle in Boozer coordinates
- Better neoclassical transport metrics than existing stellarator built with coils
- Permanent magnets + planar TF coils
- Related approaches available at high B: diamagnets or HTS saddle/dipole coils





R = 30.5 cm, B=0.15T,
A=7.2, Iota(edge) = 0.197

PRINCETON PLASMA PHYSICS LABORATORY

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

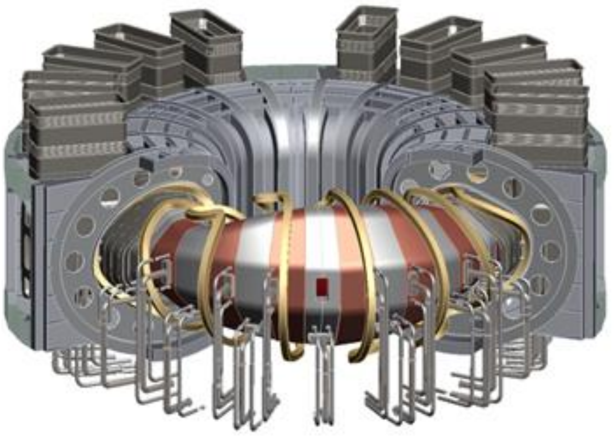
New Pilot Plant Designs Starting

- FESAC Long Range Plan identified importance of a timely Stellarator Pilot Plant design activity.
- Consistent with NASEM Report recommendations.

- Conceptual designs being developed by several groups in preparation for National Pilot Plant Team activities

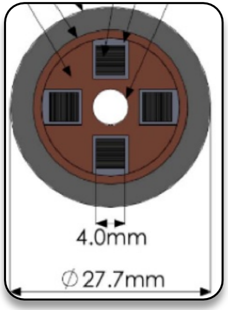
  -- PPPL: Straight outer coil-leg QA designs being combined with permanent magnets and other magnetic dipoles for good maintenance and physics properties

  -- U. Wisconsin: WISTELL-A and −B optimized QH designs (A. Bader et al)



STELLARATORS: BEST SUITED FOR POWER PLANTS

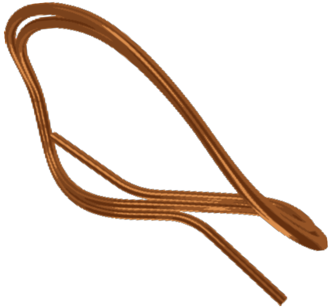
- Type One Energy is leveraging breakthrough technologies to accelerate fusion energy
  - Modern manufacturing for high-precision fabrication of high-complexity components
  - HTS magnets for higher fields
  - Advanced configuration optimization to maximize performance
- We are targeting rapid demonstration of net energy gain
  - Q>1 with conservative physics: no improvements needed to what has been achieved
  - Physics optimization can access enormous upside: Q=∞
  - Parallel development of reactor technologies to enable a pilot plant in the 2030's
- Retiring key HTS risks in partnership with MIT, CFS and UW-Madison under ARPA-E grant



MIT HTS 'VIPER' cable modified to permit bend radii < 10 cm

HTS non-planar cable with typical curvatures tested at 77 K with no loss of critical current density

Work underway to fabricate a two-turn model coil with 3D printed metal support plates



Summary: Substantial Progress on Path

- W7-X: validation of design approach, reducing neoclassical transport to sub-dominant
- W7-X: demonstration of stable detached divertor operation
- LHD: Ti(0), Te(0) ~10 keV in D operation
- Demonstration of methods to reduce ITG / TEM turbulence
- New optimization strategies to reduce turbulence, eliminate fast ion losses
- New methods to simplify stellarator coils, using permanent magnets, HTS, and related approaches

It is time for a detailed Stellarator Pilot Plant design activity (FESAC LRP, NASEM)

Private companies are forming to advance the Stellarator approach.